

# The outer halos of elliptical galaxies

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**Abstract** Recent progress is summarized on the determination of the density distributions of stars and dark matter, stellar kinematics, and stellar population properties in the extended, low surface brightness halo regions of elliptical galaxies. With integral field absorption spectroscopy and with planetary nebulae as tracers, velocity dispersion and rotation profiles have been followed to  $\sim 4$  and  $\sim 5 - 8$  effective radii, respectively, and in M87 to the outer edge at  $\sim 150$  kpc. The results are generally consistent with the known dichotomy of elliptical galaxy types, but some galaxies show more complex rotation profiles in their halos and there is a higher incidence of misalignments, indicating triaxiality. Dynamical models have shown a range of slopes for the total mass profiles, and that the inner dark matter densities in ellipticals are higher than in spiral galaxies, indicating earlier assembly redshifts. Analysis of the hot X-ray emitting gas in X-ray bright ellipticals and comparison with dynamical mass determinations indicates that non-thermal components to the pressure may be important in the inner  $\sim 10$  kpc, and that the properties of these systems are closely related to their group environments. First results on the outer halo stellar population properties do not yet give a clear picture. In the halo of one bright galaxy, lower  $[\alpha/\text{Fe}]$  abundances indicate longer star formation histories pointing towards late accretion of the halo. This is consistent with independent evidence for on-going accretion, and suggests a connection to the observed size evolution of elliptical galaxies with redshift.

## 1 Introduction

There are indications that the outer halos of bright elliptical galaxies formed later and through different processes than their inner parts. It is clearly important to establish whether this is true for some, most, or all ellipticals. Signatures of the formation

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processes may be preserved longer in the outer halos than in the well-mixed inner parts, because of the longer dynamical time-scales at large radii. Owing to the low surface brightness in these halos, the outer kinematics and stellar population properties can be best studied in local galaxies. Combining the results with predictions from simulations and with high-redshift studies of ellipticals one may expect to obtain a global picture of halo formation in elliptical galaxies. The following sections will discuss some recent results on the stellar distribution and kinematics in the outer halos (§2), the dark matter distribution and dynamics (§3), and finally the stellar populations and assembly history of nearby elliptical galaxy halos together with related results from high-redshift studies and simulations (§4).

The subject of the outer halos of ellipticals is one that has benefitted enormously from the vision of Ken Freeman, whose scientific work we celebrate with this conference. Ken was one of the first to realize the potential of using planetary nebulae (PNe) as kinematic tracers in regions where the surface brightness is too low for traditional absorption line spectroscopy. In 1987, in the course of a project with X. Hui, H. Ford and M. Dopita, he measured the first PN radial velocities in the halo of Centaurus A, the nearest elliptical galaxy, using a multi-fiber instrument at the Anglo-Australian Telescope. Together with later AAT and CTIO measurements, they were able to obtain 433 PN velocities in this galaxy (Hui et al. 1995). Together with M. Arnaboldi and others, he extended this work to the fainter PNe in the halos of more distant ellipticals such as NGC 1399, M86, and NGC 1316 (Arnaboldi et al. 1994, 1996, 1998), in order to constrain the kinematics and dark matter mass distribution in these galaxies.

The potential shown by these papers led to the idea of a special-purpose instrument, the Planetary Nebula Spectrograph (PNS), which is based on the principle of using counterdispersed imaging to simultaneously find PNe and measure their radial velocities (Douglas et al. 1997, 2002). This instrument is currently mounted at the William Herschel Telescope in La Palma. As two highlights, some 2600 PN velocities were measured in nearby M31 (Merrett et al. 2006), and within a still ongoing project  $\sim 100$ -200 PN velocities have so far been obtained for each of a sample of some 15 ellipticals (Coccato et al. 2009). The 1996 paper on M86 also reported three discrepant PN velocities, ascribed to the intracluster stellar population in Virgo. Since then, Ken has enthusiastically participated in using PNe to study the dynamics of intracluster stars in nearby galaxy clusters (Freeman et al. 2000); see also M. Arnaboldi's paper in this volume. For the first multi-slit imaging observations of PNe in the Coma cluster (Gerhard et al. 2005) he went observing at the Subaru telescope. Ken is a coauthor of some 30 refereed papers related to the use of PNe for kinematic measurements, including also the Galactic bulge (Beaulieu et al. 2000) and, again, Centaurus A (Peng et al. 2004).

## 2 Density distribution and kinematics of outer halo stars

Accurate brightness profiles over large radius ranges were constructed by Kormendy et al. (2009) for Virgo cluster elliptical and spheroidal galaxies. The brightest elliptical galaxies in this sample have profiles characterized by large Sérsic indices  $n \simeq 4 - 12$ , large effective radii  $R_e > 10$  kpc at faint surface brightnesses,  $\mu_{e,V} \simeq 23 - 25$ , and central cores (depressions relative to the Sérsic profile). Fainter ellipticals have Sérsic indices  $n \sim 2-4$ ,  $R_e$ 's of a less than a few kpc,  $\mu_{e,V} \simeq 19 - 22$ , and central cusps (extra light relative to the Sérsic profile). While the dichotomy in the central profiles of both classes is clear and is their primary distinction, there are some transition cases in the large-radius profiles. The important point for this talk is that the (bright) core ellipticals have the most extended luminous halos, and that within each of the two classes  $n$  (extent) does not correlate with luminosity (Caon et al. 1993; Kormendy et al. 2009).

Outer halo kinematics based on PN velocities were analyzed by Coccato et al. (2009) for a sample of 15 early-type galaxies. These data typically reach to  $\sim 5R_e$  and in some galaxies to  $8R_e$ . The derived profiles of PN number distribution and kinematics agree with surface brightness and absorption line kinematics where the data sets overlap, within their respective errors. The radial profiles of mean rms velocity  $v_{\text{rms}}$  for this sample fall within two groups, with part of the galaxies having slowly decreasing  $v_{\text{rms}}(R)$  and the remainder having steeply falling  $v_{\text{rms}}(R)$ . There is a large overlap of these groups with the core and cusp ellipticals, respectively (Kormendy et al. 2009; Hopkins et al. 2009a,b). The outer halos of ellipticals tend to be more rotationally dominated than the central parts. The slow-rotator versus fast-rotator classification of Emsellem et al. (2007) based on inner Sauron data is largely preserved in the halos; however, some more complex profiles of specific angular momentum parameter  $\lambda_R$  are seen in the halos. Slow rotators typically reach  $\lambda_R \simeq 0.1$  in their outer parts. Lastly, twists and misalignments in the velocity fields, commonly interpreted as signs of triaxiality, seem to be more frequent at large radii (Coccato et al. 2009).

Proctor et al. (2009) have pioneered a technique to measure absorption line kinematics for the integrated halo stellar population using data from multi-object slitless spectroscopy, and to construct 2D velocity fields to  $3R_e$  from these data. They find a variety of stellar rotation profiles beyond  $1R_e$ , constant, decreasing, and increasing, confirming that the fast-slow rotator classification may be more complicated in the halos than within  $R_e$ . Halo kinematics obtained with integral field units (IFUs) such as Sauron and VIRUS-P reach somewhat further, to  $\sim 4R_e$  (Murphy & Gebhardt 2007; Weijmans et al. 2009). In these studies, the signal from many lenslets or fibers is co-added to increase the signal-to-noise. Because of the limited field-of-view, several IFU fields may need to be exposed. For the galaxies where kinematics is available both from these absorption line techniques and from PNe, the velocity dispersion profiles agree within the errors. The integrated light techniques yield measurements also of the line profile shape parameters, giving valuable constraints on the anisotropy of the halo orbit distribution. These are harder to obtain from PNe

unless large samples can be obtained. Since PNe can be found out to larger radii, the best dynamical constraints will come from combining both techniques.

The extreme outer halo of the Virgo-centric giant elliptical galaxy M87 was studied by Doherty et al. (2009). They used small samples of PNe in fields at 60 and 150 kpc to measure the velocity dispersion, after removing Virgo intracluster stars. PNe centered around the systemic velocity of M87 were found only out to 150 kpc, but not further, and the velocity dispersion profile was found to decline steeply towards the outer edge. Given that the X-ray-determined mass profile is rising steeply at these radii and is dominated by the cluster, this is dynamically possible only if the halo of M87 is truncated. McNeil et al. (2010) studied the central bright galaxy in the Fornax cluster, NGC 1399. Again using PNe, they found that a component of low-velocity PNe (by  $\sim 800 \text{ km s}^{-1}$ ) is superposed on the main galaxy population. When this component is removed, the velocity dispersion profile of NGC 1399 is flat at  $\sim 200 \text{ km s}^{-1}$  from PNe and red globular clusters out to 80 kpc. Both studies show that the outermost halos of elliptical galaxies are in interaction with the environment, and that discrete tracers are important to disentangle the different (mixed and unmixed) components in the velocity distribution.

### 3 Dark matter and dynamics

The dark matter distribution in elliptical galaxies can be studied with a variety of techniques, including strong and weak lensing, X-ray emitting hot gas, and dynamics. The lensing results are discussed in K. Kuijken's talk in this volume; in brief, while with weak lensing data the dark halos of elliptical galaxies can be followed to hundreds of kpc, the strong lensing analyses give accurate mass measurements within the Einstein radius, and together with central velocity dispersions constrain the slopes of the mass density profiles to an average value of very nearly  $-2$  (isothermal), with small scatter.

Early dynamical analysis of stellar velocity dispersions and line profile shape data with non-parametric spherical models first indicated that the inner circular velocity curves (CVC) of elliptical galaxies are flat to  $\sim 10\%$ , out to approximately  $1-2 R_e$  (Kronawitter et al. 2000; Gerhard et al. 2001). Recent work by Thomas et al. (2007) on a sample of ellipticals in the Coma cluster with slightly more extended data ( $1-3 R_e$ ) has shown more varied CVC slopes, with some falling, some flat, and some rising. Using axisymmetric Schwarzschild models to constrain the dark matter halos in the Coma ellipticals, Thomas et al. (2009) found that the dark matter densities in these galaxies are on average  $7\times$  higher than in spiral galaxies of the same luminosity, and  $13\times$  higher than in spirals of the same baryonic mass, consistent with the earlier analysis of round nearby galaxies by Gerhard et al. (2001). Baryonic contraction is not sufficient to explain the difference, implying that the inner halos of ellipticals presumably formed earlier than those of spiral galaxies. If one assumes that the halo densities measure the density of the Universe at the time of collapse (Gerhard et al. 2001), the assembly redshift ( $1 + z_{\text{ass}}$ ) for the Coma ellipti-

cals is twice that for typical spiral galaxies, and puts their  $z_{\text{ass}} = 1...3$  (Thomas et al. 2009), with brighter ellipticals assembling later.

Several intermediate-luminosity ellipticals have steeply falling outer PN velocity dispersion profiles (Romanowsky et al. 2003; Coccato et al. 2009). The prototype galaxy for this class is NGC 3379, for which some 200 PN velocities are available. It was thus argued (Romanowsky et al. 2003; Douglas et al. 2007) that this galaxy might be ‘naked’, i.e., lack a significant dark matter halo. Extensive recent dynamical modeling by de Lorenzi et al. (2009), using the made-to-measure particle code NMAGIC (de Lorenzi et al. 2007), has shown that a variety of dark matter halos are allowed by the data, implying radially anisotropic orbit distributions, and that the no-dark matter halo is ruled out (see also Weijmans et al. 2009). However, the allowed halo density distributions imply that the CVC in this galaxy falls by at least 25% between the center and  $2R_e$ , i.e. they are of significantly lower density than would be required for a flat CVC. Similar results were found for two other galaxies of this class, NGC 4697 and NGC 4494 (de Lorenzi et al. 2008; Napolitano et al. 2009).

There is a long history of mass determination in X-ray bright elliptical galaxies, using the hot gas as a tracer in assumed hydrostatic equilibrium in the gravitational potential (e.g. Nulsen & Böhringer 1995; Humphrey et al. 2006; Fukazawa et al. 2006; Nagino & Matsushita 2009). Based on a comparison of the gravitational potentials and circular velocities inferred from X-rays and from dynamics, Churazov et al. (2008, 2010) argued that the non-thermal sources of pressure contribute on average 20-30% of the thermal gas pressure. Das et al. (2010) recently devised a non-parametric Bayesian technique to determine CVCs and confidence ranges from de-projected hot gas pressure and temperature profiles. Comparing with dynamical mass determinations, they also find differences indicating that non-thermal pressure sources are important in the central 10 kpc of their analyzed six galaxies. Other possible interpretations for these differences are violations of hydrostatic equilibrium or biases introduced by the assumptions in the dynamical models; this is an important issue that needs to be clarified. The dark matter mass fractions inferred by Das et al. (2010) are 35 – 80% at  $2R_e$ , rising to 80 – 90% at the outermost radii. Das et al. (2010) also find that for all of their galaxies the outer CVCs are rising, implying steeper than isothermal mass profiles. Furthermore, the inferred circular velocities and the luminosities of their galaxies are found to correlate with the velocity dispersion of the environment. Both results suggest that the properties of X-ray bright ellipticals are closely related to their group environments.

## 4 Stellar population and assembly history

Studies of the stellar populations in the outer halos of early-type galaxies may give important constraints on their assembly history. Due to the faint surface brightnesses in the outer regions this work is only in its beginning, requiring large telescopes and/or special techniques.

In a recent study, Coccato et al. (2010a) used deep medium resolution spectroscopy with FOCAS at the Subaru telescope to measure Lick line-strength indices far into the halo of one of the two Coma brightest cluster galaxies (BCGs), NGC 4889. Combining these with literature data, Coccato et al. (2010b) constructed radial profiles of metallicity,  $[\alpha/\text{Fe}]$  abundance ratio and age, from the center out to  $\sim 60$  kpc ( $\sim 4R_e$ ). These profiles show evidence for different chemical and star formation histories for stars inside and outside  $\sim 1.2R_e = 18$  kpc radius. The inner regions have a steep metallicity gradient and high  $[\alpha/\text{Fe}]$  at  $\sim 2.5$  solar value, pointing to a rapid formation process. This is consistent with a quasi-monolithic, dissipative merger collapse at early redshifts (Kobayashi 2004), followed by one or at most a few dry mergers between several such units so that the original steep metallicity gradient (Chiosi & Carraro 2002; Pipino et al. 2008) was only partially erased (di Matteo et al. 2009). In the halo of NGC 4889, between 18 and 60 kpc, the metallicity is near-solar with a shallow gradient, while  $[\alpha/\text{Fe}]$  shows a strong negative gradient, reaching solar values at 60 kpc, and the inferred ages are 9-13 Gyr. This argues for later accretion of stars from old systems with more extended star formation histories (Matteucci 1994), presumably through minor mergers from the galaxy's group environment (Abadi et al. 2006; Naab et al. 2009).

Rudick et al. (2010) study the colour distribution in the outer halo of M87 and the adjacent intracluster light. They find that the M87 halo becomes bluer with radius to the outermost radii, and argue that the common colours of the outer halo and of some surrounding intracluster tidal features suggest that the galaxy's envelope may have formed from similar streams. Foster et al. (2009) used the technique from Proctor et al. (2009) to study three galaxies. Their most extended dataset is for NGC 2768 which they suggest, based on comparison with simulations by Hopkins et al. (2009a), is consistent with a dissipative merger origin. The two other datasets have too large errors beyond  $R_e$  to allow firm conclusions. Weijmans et al. (2009) find from co-added Sauron field data that the metallicity gradients in the two intermediate luminosity ellipticals NGC 3379 and NGC 821 remain approximately constant to  $4R_e$ , with old and subsolar metallicity populations in the halos. Thus outer halo stellar population studies to date do not yet combine to a clear picture.

The bimodal stellar populations found by Coccato et al. (2010b) in the core and outer halo of NGC 4889 are consistent with recent results on the size evolution of early-type galaxies (ETGs) with redshift (e.g. Daddi et al. 2005; Trujillo et al. 2007; Cimatti et al. 2008), such that ETGs at  $z \sim 1$  ( $z \sim 2$ ) have sizes a factor of 2 (3 – 5) smaller than ETGs with similar mass today (van der Wel et al. 2008; van Dokkum et al. 2008; Saracco et al. 2009). Recently, van Dokkum et al. (2010) find from stacked rest-frame R-band images that massive ETGs have nearly constant mass inside 5 kpc with redshift, but increase their envelope mass by a factor  $\sim 4$  since  $z = 2$ , with effective radius evolving as  $R_e \propto (1+z)^{-1.3}$ . Minor mergers may play an important role in this process (Naab et al. 2009), and the accreted galaxies are likely to have gone through longer star formation histories, leading to less  $\alpha$ -enriched stellar populations as was found in the halo of NGC 4889. Further work on the stellar populations in the outer halos of local elliptical galaxies may

become a valuable tool to understand what part of the elliptical galaxy population participates in the observed size evolution.

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